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Research article

Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions

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A R T I C L E I N F O

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A B S T R A C T

Sanitation access in urban areas of low-income countries is provided through unstandardized onsite technologies containing accumulated faecal sludge. The demand for infrastructure to manage faecal sludge is increasing, however, no reliable method exists to estimate total accumulated quantities and qualities (Q&Q) This proposed approach averages out complexities to estimate conditions at a centralized to semi-centralized scale required for management and treatment technology solutions, as opposed to previous approaches evaluating what happens in individual containments. Empirical data, demographic data, and questionnaires were used in Kampala, Uganda to estimate total faecal sludge accumulation in the city, resulting in 270 L/cap·year for pit latrines and 280 L/cap·year for septic tanks. Septic tank sludge was more dilute than pit latrine sludge, however, public toilet was not a distinguishing factor. Non-household sources of sludge represent a significant fraction of the total and have different characteristics than household-level sludge. Income level, water connection, black water only, solid waste, number of users, containment volume, emptying frequency, and truck size were predictors of sludge quality. Empirical relationships such as a COD:TS of 1.09 ± 0.56 could be used for more resource efficient sampling campaigns. Based on this approach, spatially available demographic, technical and environmental (SPA-DET) data and statistical relationships between parameters could be used to predict Q&Q of faecal sludge.

1. Introduction

The current state of sanitation in urban areas of low- and middle-income countries is 2.8 billion people served by onsite sanitation, with the majority of excreta not safely managed. For example only 37% safely managed in 12 reported cities (Peal et al., 2014; WHO and UNICEF, 2017). However, the definition of onsite sanitation and faecal sludge is very broad, meaning only that it is not connected to or transported in a sewer (Strande et al., 2014). Hence, the reality is a chaotic mixture of inappropriately and haphazardly constructed containment for the onsite storage of sludge, with no level of standardization (Isunju et al., 2013). For example, a simplified classification of onsite systems in Dar es Salaam, Tanzania included pit latrines that were lined, unlined, partially lined, improved, collapsed, abandoned, tanks that were fully lined ("septic tank", "storage tank"), partially lined ("cess pit"), with no drainage, or drainage going to soakaway, open drain, overflow, water body, soakaway, or soil (Brandes et al., 2015). This status is the result of many factors, including a lack of tenure or ownership in slums, government involvement, financial resources, heterogeneous settlement patterns, and a strong focus of the Millennium Development Goals (MDGs) ending open defecation, but not developing management plans for what happens when onsite storage of sludge becomes full (Beyene et al., 2015; Günther et al., 2011; Moe and Rheingans, 2006; Oyoo et al., 2013; Tilley et al., 2014). It is commonly perceived that faecal sludge management is simpler than centralized sewer based solutions, as it involves the management of simpler technologies. Although faecal sludge management can be less expensive, it is in reality much more complicated (Dodane et al., 2012). In addition to the diversity of sludge containment types, it requires the active and complex management of personal, financial, political, legal,

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and socio-cultural interactions along the entire service chain (Chowdhry and Koné, 2012). Treatment is difficult due to wide-ranging characteristics and stabilization, which dictate selection of technical solutions, govern settling and dewatering, and influence treatment efficacy (Appiah-Effah et al., 2014; Bassan et al., 2013; Dodane et al., 2012; Gold et al., 2016; Kengne et al., 2014; Sonko et al., 2014).

Immediate solutions are needed, while in parallel developing more sustainable solutions for the future (Moe and Rheingans, 2006). This includes collection, transport and treatment of faecal sludge on a decentralized, semi-centralized, or centralized scale. Acknowledgment of the importance of faecal sludge management by governments, development agencies, municipalities, and academia is rapidly increasing, and has now been included in the Sustainable Development Goals (SDGs) (Bassan and Strande, 2011; Chowdhry and Koné, 2012; FSM Toolbox, 2017; The World Bank Group, 2016). The result is that funding is starting to become available for infrastructure. However, with the current status, reliable estimates of faecal sludge quantities and qualities (Q&Q) for the design of treatment technologies and management solutions are nearly impossible. Hence, studies are rare that quantify both Q&Qs of faecal sludge, which are necessary to estimate loadings (Fanyin-Martin et al., 2017; Ross et al., 2016). Therefore, engineers try to make reasonable estimates when designing solutions, but typically without adequate resources or time. The result is treatment plants that are immediately at capacity (e.g. Lubigi in Kampala, Uganda) (Fichtner and Associates, 2008), or way under- or over-capacity (Bassan and Strande, 2011). Inadequately sized treatment and management solutions impact operation and are a direct risk to public health.

In comparison, extensive research has gone into developing influent generator models for the design and optimization of wastewater treatment facilities, leading to quite sophisticated empirical and fundamental models. Typical model parameters include average water usage, climate data, wet and dry flows, population equivalents, soil type, length and type of sewer, and industrial inputs (Flores-Alsina et al., 2014; Martin and Vanrolleghem, 2014). Models also consider biological activity and homogenization during transport in sewer. Homogenization in sewers is significant, with even random peaks of contaminants from individual households flattened out as bell-shaped curves (Ort et al., 2005). The variation that enters treatment plants can then be modeled harmonically, with diurnal, weekly, and yearly variations (Langergraber et al., 2008).

However, this experience is not transferable to faecal sludge management, and developing solutions based solely on experience with centralized wastewater treatment in industrialized countries will result in inappropriately designed systems that are prone to failure (Bassan et al., 2015). The development of sophisticated influent wastewater models required massive operating data, with further advances limited by prohibitive resource and financial constraints of data collection (Martin and Vanrolleghem, 2014). In contrast to over 100 years of operating experience in wastewater, faecal sludge management is in its infancy, for example in the United States where 25% of sanitation is non-sewered, the USEPA only acknowledged it as a long-term solution within the last 20 years (USEPA, 2005). In addition, faecal sludge is one to two times higher in COD and TS magnitude and variability than wastewater (Gold et al., 2017). The variability is due to the differences in onsite containment technologies, retention times, household usage patterns, quality of construction, collection practices, and that it is collected batch-wise individually, and not homogenized during transport in a sewer (Strande et al., 2014; USEPA, 1984). The few attempts in the literature to model faecal sludge at scale have attempted to use numerical modeling of a mass balance approach, using data from individual pit latrines in an attempt to predict average values for a neighborhood or city (Brouckaert et al., 2013; Kimuli et al., 2016; Lugali et al., 2016; Todman et al., 2015).

Hence, there is a desperate need to develop reliable, empirical, field-based methods for the estimation of faecal sludge Q&Q at scales relevant for the design of treatment technologies and management solutions. The objective of this study was to fill that gap by developing a method of data collection and field-testing it in Kampala, Uganda. The use of statistical trends in spatially available (SPA) data based on in-field-questionnaires and demographic, environmental and technical (DET) data to measured parameters were investigated for upscaling results of data collection to regional areas.

2. Materials and methods

2.1. Overview

The method for data collection is based on the hypothesis that types of demographic, environmental and technical (DET) data that can be spatially analyzed (SPA), can be used as predictors of faecal sludge Q&Q. It is important to note these are correlations or statistical relationships, not necessarily causation, but if consistent relations are observed, they can be used as predictors. The steps taken included researching available types of SPA-DET, developing a context specific questionnaire that was used to interview customers and service providers during both emptying operations and sludge delivery, development of a sampling plan, and data analysis, as described in more detail in the following section.

2.2. Spatially analysable demographic, environmental and technical (SPA-DET) data

This research was conducted in Kampala, Uganda. Kampala has a population of 1.5 million (UBOS, 2014), which doubles during the day due to commuting populations (Kulabako et al., 2010). Of the city's residents, 92.5% are served by onsite sanitation technologies (Fichtner and Associates, 2008) and there are two existing treatment plants. Income category was the main type of SPA-DET that was obtained from the Kampala Capital City Authority (KCCA, 2012). Additional types of environmental information (e.g. groundwater, soils) were not available.

2.3. Questionnaire

The questionnaire collected information on 14 hypothesized indicators of faecal sludge Q&Q. The questionnaire included the following questions to the driver: what is the volume of your truck; who does the truck belong to; is your truck completely full (following the emptying event); was the customer's onsite faecal sludge containment fully emptied; did you add any water to the onsite faecal sludge containment; what is the source/origin of sludge (i.e. household, multiple household, institution/industry, hotel/restaurant, school, public toilet, other); and was the faecal sludge containment a lined pit latrine, or septic tank. The questionnaire included the following questions to the customers: if a household, number of inhabitants; types of wastewater entering system (i.e. toilet, bathing/washing, kitchen, other); does solid waste enter the faecal sludge containment, yes or no; if yes, what types (e.g. hygenic products, food waste, other); age of faecal sludge containment (i.e. years $0 \leq 5$, $5 \leq 10$, $10 \leq 20$, > 20); do you have access to a water connection; volume of containment; have you ever had the faecal sludge containment emptied, when; is the containment watertight; and if septic tank, how many chambers.

2.4. Sampling plan

From December 2013 to March 2014, which includes both the dry and (short) rainy season, 180 faecal sludge samples were collected during emptying events by vacuum trucks, at the locations presented in Fig. 1. Samples were collected from a diverse range of sites representing single and multiple households, public toilets, schools, institutional/commercial/industrial, restaurants/hotels, and containment technologies (i.e. septic tanks and pit latrines). Samples were not collected from